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PROMOTING SUSTAINABILITY IN EMERGING ECONOMIES VIA LIFE CYCLE THINKING

Thai national life cycle inventory readiness for product environmental footprint

Nongnuch Poolsawad[1] · **Wanwisa Thanungkano**[1] · **Jitti Mungkalasiri**[1] · **Ruthairat Wisansuwannakorn**[1] · **Prakaytham Suksatit**[1] · **Athiwatr Jirajariyavech**[1] · **Kittipoj Datchaneekul**[1]

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Abstract
Purpose In the near future, the products of Thai industries and companies mainly producing parts and products for export to the European Union (EU) will require the Product Environmental Footprint (PEF) to assess the environmental performance and resource efficiency of products by using a life cycle perspective. The potential generic (often used interchangeably with background data) data have to be modified and improved for mandatory use in the product-specific and country-specific PEF database.
Methods PEF is used as a tool for assessing the environmental burden of products and services for export to the EU. It requires both specific data from primary sources and generic data to fulfill assessment requirement. Accordingly, the Thai national life cycle inventory (LCI) database plays a key role in generic data that was used to evaluate the environmental performance of products. This paper presents the perspective of Thai data readiness for PEF in which the quality of LCI is the main issue of concern. The current situation of the Thai national LCI database was reviewed. Then, the gaps of data were addressed, and the gaps were also filled. Non-representative data and untreated waste are the selected issues that were presented in this paper.
Results and discussion Many gaps were revealed for the Thai national LCI database because this database was developed based on ISO 14040/44, which may not be compliant with the PEF guide. The issues that have been selected for improvement are non-representative data and untreated waste because these gaps can offer inaccuracy concerning the environmental burden of products potentially leading to the reliability of products for export to the EU. However, the Thai national LCI database has not achieved the data quality aspects of the PEF, continuously improving the quality of data to meet the requirements of the PEF.
Conclusions The lessons learned from the real-world situation of data quality development based on PEF requirements were extracted. The practical procedure and recommendations were transparent for drivers and researchers who would like to start with data quality issues and prepare for the EU single market.

Keywords Data quality · Non-representative data · Product Environmental Footprint (PEF) · Thai national LCI database · Untreated waste

Responsible editor: Shabbir Gheewala

✉ Nongnuch Poolsawad
nongnucp@mtec.or.th

[1] Life Cycle Assessment Laboratory, National Metal and Materials Technology Center (MTEC), Pathum Thani 12120, Thailand

1 Introduction

Thailand is an export-dependent country where economy exports account for approximately 65% of the gross domestic product (GDP). In 2014, the value of export products stood at US$56 million, and the main exports were manufactured and agricultural products with China, Japan, the USA, and the European Union (EU) as the key export partners (Economic Outlook 2015). Therefore, the EU single market policy will make more of the opportunities and threats in many countries, including Thailand. After the launching of the single market, non-tariff barriers (NTBs) will continue to bedevil trade between member states in 2017. NTB trade is constrained within free trade areas, even in the absence of tariffs. Thailand will be affected by the NTBs with restricted foreign trade within the EC as Thailand faces a highly competitive market with a broad range of sellers in EU markets.

For instance, an export subsidy to a domestic manufacturer has a similar trade distorting the effects as a tariff on imported products, because the subsidy indirectly protects domestic producers from foreign competition. A product standard or an environmental regulation requiring products to be manufactured domestically, therefore, restricts access to foreign product standards and effectively hinders trade. In essence, within the global system of free trade, policymakers are tempted to protect domestic manufacturers who are no longer protected by tariffs and induce policies that impose NTBs instead (EPRS 2014).

In this study, the results from the gap analysis of the current Thai LCI database towards Product Environmental Footprint (PEF) compliance (STI 2014) were analyzed and will be presented in Sect. 3. However, this paper presents the main issues of the Thai national LCI database and aims to prepare and support Thailand export industries in entering the EU single market by using PEF (EC 2013) as a tool for evaluation. LCI data is the skeleton outline for conducting the PEF study, which requires reliable data to assess the quality of products from an environmental perspective. The paper is structured as follows: Sect. 2 presents a comparison of PEF requirements and ISO 14044 with the aim of closing the gap of the Thai national LCI database, and Sect. (3) demonstrates the current status of the Thai national LCI database with the aim of improving the gap of the Thai national LCI database in Sect. (4). Thai national LCI for the PEF and PEF data quality requirements will be shown in Sect. (5). Discussion and learning from LCI database of Thailand and ended up with a conclusion in Sect. (6).

2 Comparison life cycle approach of PEF with ISO 14040

ISO 14040/44 (ISO 14040:2006 2006; ISO 14044:2006 2006) are the globally accepted standards for life cycle-based environmental assessments. The EC PEF (EC 2013) method provides a greater degree of methodological consistency and establishes unambiguous requirements, thereby facilitating increased consistency, comparability, and reproducibility of the results (Manfredi et al. 2015). The environmental footprint method requires full life cycle accounting and accommodates a broad range of relevant environmental performance indicators in order to decrease the probability of burden shifting (Manfredi et al. 2015).

According to the list of requirements shown in Table 1, the Thai national LCI database can improve data quality. Although the present paper cannot demonstrate every issue, it does address the criteria on the boundaries for the evaluation of the potential of the generic data (often used interchangeably with background data).

This paper presents the readiness of the Thai national LCI database prepared for use in the PEF. This paper aims to improve the quality of data, especially the generic data for ISO 14040 and ISO 14044 which represents the main framework and methodology of the LCA (ISO 14040:2006 2006; ISO 14044:2006 2006). Furthermore, the PEF guide has been used to perform data quality. The readiness of the Thai national LCI database can be divided into two main issues, including challenges on data quality development and generic data improvement. First, the challenges for improved quality of LCI data are noticeable. Consequently, PEF requirements will present the criterion set for Thai generic data. Second, the generic data will be improved through modifying non-representative data and untreated waste.

3 Current status of Thai national LCI database

The pathway of the Thai national LCI database was developed in 1990. In 2003, a pilot project was proposed for the LCI/LCA and supported by the Japanese government (Poolsawad et al. 2015). At the time, LCI datasets used non-national databases as generic data as shown in Fig. 1. Since 2006, numbers from the Thai national LCI datasets have been published and implemented in diverse projects. Presently, 515 national gate-to-gate (G-to-G) and 515 national cradle-to-gate (C-to-G) datasets across different industrial sectors where electricity, water supply, energy, materials, transport, agricultures, and waste treatment are developed and continuously improved (Poolsawad et al. 2015). Undoubtingly, LCI is the most significant tool for evaluating the environmental impacts of any environmental assessment tools.

The clearly identifiable problem appearing in Fig. 1 continues to be the waste flow. Although waste flow seems to be a minor issue, it remains unacceptable and must be eliminated. The vision is to help provide data quality procedures on Thai national LCI databases with attempts to improve the data in order to meet PEF requirements. In this section, the current status and its gaps are demonstrated in Table 2. Taking into account this uncertainty and quality of the input in the LCA study reinforces the confidence in the results and contribute to the decision-making process based on the results and their interpretation by quantitative and qualitative methods. The nature and extent of the uncertainties in the LCA are such that formal methods for dealing with the aforementioned are truly challenging. Inadequate treatment of uncertainty is one cause of this confusion. The reliability of the results yielded by these assessment methods depends largely on the quality of the inventory data.

The aforementioned findings undoubtedly clarify room for improvement in all compliance areas of the PEF with reference to Table 1. Consequently, this amplification of tone raises difficulties; attempts have been made to prioritize and handle

Table 1 Comparison of EC PEF with ISO 14044:2006 (EC 2013; ISO 14040:2006 2006; Manfredi et al. 2015; Weidema 2013; EC 2010)

Requirements/criterion	EC PEF	ISO 14044:2006
Life cycle approach	Based on life cycle thinking approach	Based on life cycle thinking approach
Applicability of results	In-house applications	• Identify opportunities to improve the environmental performance of products
	• External applications (both B2B and B2C)	• Provide relevant information to decision-makers
	• Comparisons and comparative assertions supported	• Comparative assertions supported
Definition of functional unit	• Requires the functional unit called "unit of analysis"	• Consists of goal and scope of the study
	▪ Function(s)/service(s) provided: "what"	▪ Provides a reference unit in a life cycle assessment study, which be clearly defined and measurable
	▪ Extent of the function or service: "how much"	▪ Quantified performance of a product system
	▪ Expected level of quality: "how well"	
	▪ Duration/life time of the product: "how long"	
	▪ CPA/NACE code	
Scope of the evaluation	• Cradle-to-grave approach	• System boundaries are defined based on the goals and scope of the study
	• Processes included in the system boundaries can be divided into foreground and background processes	• Cutoffs are allowed and can be based on mass, energy, or environmental significance
	• No cutoffs allowed	
Primary data collection	• Requires primary data collection called "specific data" from the foreground processes, which are the activities for assessing available data	• The collected data, whether measured, calculated, or estimated, are utilized to quantify the input and output of a unit process
Input data type and quality	• Minimum data quality requirements are set for both specific and generic data	• Data quality has to be evaluated based on eight criteria
	• Data quality has to be evaluated with a semi-quantitative approach provided, based on six data quality criteria derived from ISO 14044:2006 and ILCD Handbook	• No minimum data quality requirements are established
Multicriteria evaluation	• Default set of 14 mid-point impact categories and related impact assessment models provided	• No default list of impact categories of environmental issue in line with the goals and scope of the study
Solving multifunctionality problems	• Departing from ISO 14044:2006, it establishes the following decision hierarchy:	• The following decision hierarchy is established:
	▪ Subdivision or system expansion	▪ Subdivision of processes
	▪ Allocation based on underlying physical relationship	▪ System expansion
	▪ Allocation based on some other relevant relationship	▪ Allocation based on physical relationships
	• Provides detailed guidance for modeling of multifunctionality at EoL	▪ Allocation based on other relevant relationships (e.g., economic allocation)
		• No guidance for modeling of multifunctionality at EoL
Reporting elements	• Minimum reporting elements:	• Provides a list of general (mandatory) reporting elements
	▪ Summary	• Provides detailed additional reporting requirements for third-party reports as follows:
	▪ Main report	▪ Modifications to the initial scope
	▪ Annex	▪ System boundary
	▪ Confidential and proprietary information (optional)	▪ Description of unit processes
		▪ Data
		▪ Choice of impact categories
		▪ Category indicators
Evaluation of uncertainty	• Requires the provision of at least a qualitative evaluation of both data inventory uncertainty and choice-related uncertainty	• Requires the evaluation of the results' uncertainty for all studies used in support to comparative assertions intended for disclosure to the public
	• Quantitative evaluation of uncertainty is optional	• No further guidance provided
Review of the study	• Any study intended for external communication will be reviewed by an independent and qualified external reviewers (or review team)	• A panel of interested parties will conduct critical review of any LCA study to support comparative assertion intended to be disclosed to the public
	• A study to support comparative assertion(s) intended to be disclosed to the public will be reviewed by three independent reviewers	• An external independent expert may be selected by the study commissioner to act as a chairperson of a review panel of at least three members
	• Minimum requirements on reviewer qualifications apply	

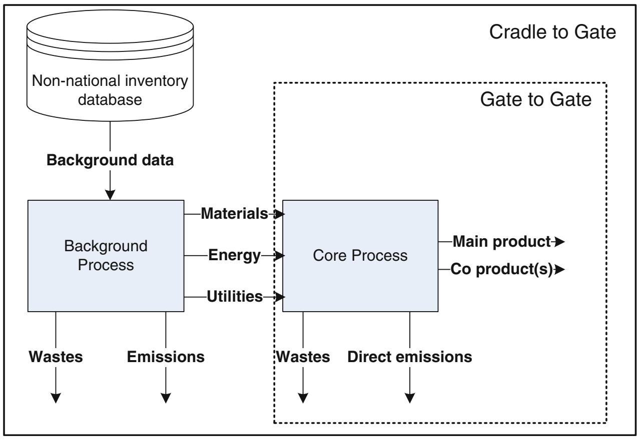

Fig. 1 Framework for the creation of Thai national LCI data before improvement

these problems to improve the quality of the Thai LCI database in the following areas:

- Documentation

  Certain issues need to be addressed for all current and future documentation. Documentation suffers from a number of potential problems. For example, doing anything right is expensive and time-consuming. In addition, there is a document problem separate from the LCI development that practitioners have failed to take seriously. Obviously, incomplete documentation can cause misleading use, while well-documented evidence must be provided for intended LCA applications. The ILCD data network entry level (International Reference Life Cycle Data System (ILCD) 2010) is selected to document the LCI data. In fact, ILCD documentation has been used for several years but does not specify documentation monitoring requirements and is not taken into account in commitments. For these reasons, the systematic check of the documentation has been set to monitor the documentation of Thai LCI data to meet the minimum requirements for ILCD compliant documentation.
- Nomenclature

  This area is not only time-consuming but also depends on the software, namely Sima Pro 7.3.3, that is used. Recently, Thai LCI data has progressively changed the nomenclature to conform with the ILCD nomenclature documentation, even though the nomenclature of elementary flows provided in the software is unable to comply with the ILCD nomenclature.

Table 2 Results of the compliance analysis of Thai national datasets against the PEF

Compliance area	Product Environmental Footprint	Compliance with PEF
Documentation	• ILCD format to be used	• No
	• Minimum documentation extent specified	• No
Nomenclature	• Compliance with ILCD nomenclature document (e.g., elementary and product flow naming, prescribed flow properties and unit groups/units for flows, classifications naming, etc.)	• No
	• Use of ILCD reference elementary flows	• No
	• Only certain aggregated elementary flows (e.g., VOC) are permitted	• No
	• PEF terminology to be used	• No
Data quality	Achieved data quality levels to be provided (subject to review) on:	• No
	• Technological representativeness	
	• Geographical representativeness	
	• Time-related representativeness	
	• Completeness	
	• Parameter uncertainty	
	• Methodological appropriateness and consistency	
	• Overall quality	
	Note: Data quality levels are well-defined	
Method	• PEF or PECR methodology compliance	• No
	• Mandatory LCIA methods fixed [4]	• No
		(No compliance but this does not much affect LCI datasets)
Review	• Review by "qualified reviewer" as defined in PEF guide [4]	• No
	• Separate review report	• Yes

- Data quality

  PEF strictly requires the quality of data to assess the environmental footprint. The data quality indicators have been assigned into six indicators as shown in Sect. 4. Significantly, PEF believes that poor data quality cannot provide reliable results on environmental impact or meet the transparent data quality requirement proposed.
- Method

  Firstly, PEF methodology requires attributional modeling and considers three more compliances, namely system boundary, end of life modeling, and multifuctionality. For Thai LCI datasets, different datasets reveal different numbers of compliances, but with constant improvement. Secondly, ILCD has been used for PEF, which relies on a mandatory LCIA method. The results from LCIA present in terms of environmental footprint (EF), which is calculated using the following equation:

$$EF_i = \sum\left(M_j \times FP_{i,j}\right) + \sum\left(T_j \times \mathrm{FT}_{i,j}\right) \qquad (1)$$

  where EF_i represents the specific environmental impact, e.g., climate change, human toxicity, water resource depletion, M_j is the amount of material j in mass or volume, $FP_{i,j}$ represents the intensity factor (or characterization factor) of environmental impact i to produce material j in a life cycle perspective, T_j is the distance between the final production of the material j and suppliers, and $FT_{i,j}$ represents the intensity factor of environmental impact i of the transportation of material j to the suppliers.
- Review

  Thai national LCI database does not face the problem of review area because the critical review process requires that a decision be made to promote the LCI data as a Thai national database (Mungkalasiri et al. 2010). Moreover, the LCI data used for PEF have been reviewed by qualified reviewers.

4 Gap to improve the Thai national LCI database

The Thai national LCI database plays an important role in the generic (background) data and is a key point in the reasons why this paper needs to concern the national database. Frequently encountered issues are as follows: (1) non-representative data and (2) untreated waste. In this section, the *diesel mix at refinery; from crude oil and biocomponents, production mix, at refinery; 50 ppm sulfur* dataset was selected to present the LCI data improvement in compliance with PEF requirements and criteria. For the comparison, 1 kg of the process of diesel mix at refinery was observed by using SimaPro 7.3.3 to analyze the compartments of inventory, including final waste flow and raw materials. In addition, the method of ILCD 2011 Midpoint+ V1.05 was applied for impact assessment following the 14 default impact categories appeared in PEF guide (EC 2013). Again, the significant results are consequently divided into the two issues below:

4.1 Non-representative data

To deal with the problem of the non-representative data and reveal the differences of environmental impacts from different sources of generic data, the differences in the non-representative data are commonly distinguished in terms of geographical, temporal, and technological differences. In this case, the diesel mix at refinery; from crude oil and biocomponents, production mix, at refinery; 50 ppm sulfur for the consideration; however, crude oil is not represented in the Thai national LCI data. Therefore, crude oil from the following three sources: (1) *average LCI data of crude oil from literature*; (2) *crude oil, at production from Nigeria;* and (3) *crude oil, at production onshore from Middle East* were selected to evaluate for coping with the non-representative data. As a result, Fig. 2 shows the impact contributions of different generic data on each environmental impact category.

Typically, the data contributing less environmental impact can be caused from incomplete LCI data, which leads to incorrect findings on environmental impact. In fact, in the diesel mix at refineries from production in Thailand, the majority of crude oil (approximately 94%) is imported from the Middle East where United Arab Emirates (UAE), Saudi Arabia, Oman, Qatar, and Yemen are represented by large volumes of import, respectively. Thailand also imports crude oil from Africa (2%), Southeast Asia (2%), and others (2%) (Bulakul 2008). It is evident, therefore, that the suitable crude oil data for the diesel mixed at refineries by production in Thailand is crude oil, at production onshore from Middle East. Two more sources of generic data show average crude oil production from literature proposing minimal impact in which some impact categories have no contribution. The main reason is that LCI data contains less input and output substances; thus, fewer emissions are addressed. Alternatively, crude oil, at production from Nigeria demonstrates high impact contribution and should not be appropriate for selection and use as generic data.

4.2 Untreated waste

Waste flow typically does not receive due attention because most production processes discharge waste into the environment. If these flows are ignored and left untreated, the environmental impacts revealed by the process were mistaken because the environmental burden from waste treatment has not been concerned. For example in the diesel mix at refinery process, Table 3 shows the list of final waste flow before treatment and a list of waste for treatment after improvement.

According to this study, the Thai national LCI database normally remains the final waste flow in the process. Table 4

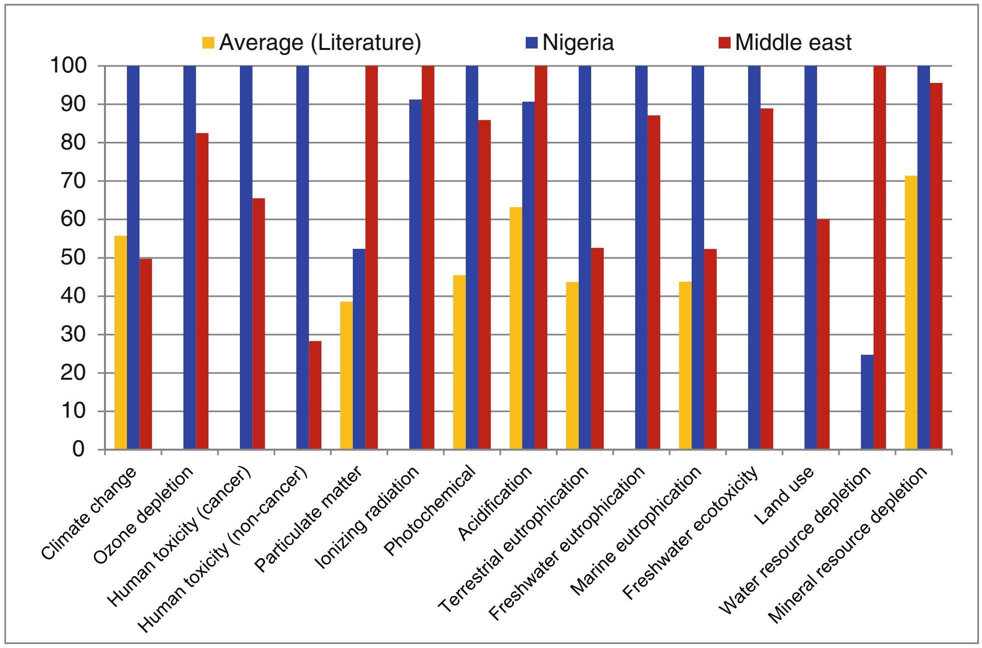

Fig. 2 Impact contributions of the process of diesel mix at refinery with 1 kg from different generic data

shows that when the LCI is created by the remaining final waste flow, several waste substances require treatment. On the other hand, if waste has been treated, the final waste flow was not observed (represented as *x*). To monitor the final waste flow, SimaPro can be used to analyze the inventory before executing the environmental impact.

Consequently, the untreated waste inventories reveal less contribution to impact. As previously mentioned, final waste flow must be treated before impact assessment. The comparison of the diesel mix at refinery process between waste treatment and no waste treatment is shown in Fig. 3.

According to the findings, the environmental impact on all impact category of waste treatment LCI dataset is higher than no waste treatment. The water resource depletion impact category notably differs in terms of impact between these two datasets. As previously indicated, the selection of generic data for non-representative data should be given greater attention and untreated waste must be unacceptable. Hence, the framework for the creation of the Thai national LCI database has been changed as represented in Fig. 4.

The framework has been modified for creation, is capable of reducing uncertainty, and gains greater confidence in the precision of the dataset as demonstrated in Fig. 5. Accordingly, the diesel mix at refinery dataset has also been selected to measure the uncertainty of data through CV (see Sect. 5.1.5) results. The results show the levels of uncertainty to have been changed, depending on the reliability of the data.

5 PEF data quality requirements

Data quality requires a set of criteria for the representativeness and completeness of the data. Resource use and emission profiles are available in specific and generic data, both of which

Table 3 Waste flow produced and waste treated from the *diesel mix at refinery* process

Final waste flow	Waste to treatment
Oily sludge	Oil sludge to special waste incinerator
Sulfur	Disposal, chemical waste to unspecified treatment
Asphalt	Disposal, asphalt, 0.1% water, to sanitary landfill
Oily contaminated solid wastes	Refinery sludge to special waste incinerator
Coke	Disposal, hard coal ash from stove, 0% water, to sanitary landfill
Chemical waste	Disposal, chemical waste to unspecified treatment
Spent catalyst	Catalyst waste in special landfill
Spent chloride absorbents	Disposal, chemical waste to unspecified treatment
Spent activated carbon	Disposal, spent activated carbon with mercury, 0% water, to underground deposit
Dry decanted oil sludge	Refinery sludge to special waste incinerator

Table 4 Comparison of waste substances requiring waste treatment

No.	Waste substance	Unit	No waste treatment	Waste treatment
1	Asphalt	kg	7.6201E-07	x
2	Catalyst waste	kg	0.000090839	x
3	Chemical waste, unspecified	kg	4.86158E-05	x
4	Coke	kg	5.0435E-06	x
5	Municipal waste landfill	kg	3.93856E-12	x
6	Oily contaminated solid wastes	kg	0.000004485	x
7	Oily sludge	kg	0.000129025	x
8	Plastic waste	kg	1.57338E-10	x
9	Radioactive tailings	kg	2.5177E-17	x
10	Rubbles	kg	3.13112E-10	x
11	Slags	kg	4.03881E-07	x
12	Sludge	kg	2.36071E-09	x
13	Soil waste	kg	8.31085E-06	x
14	Stones and rubble	kg	4.96784E-15	x
15	Sulfur	kg	1.7331E-06	x
16	Waste, industrial	kg	1.44924E-05	x
17	Waste, nuclear, low-level active	kg	2.52749E-13	x

require quality assessment. Semi-qualitative and qualitative methods are provided for PEF study for assessing the quality of data. The semi-qualitative method has six data quality criteria for calculating the level of the data quality on dataset or process. On the other hand, qualitative data (also called "expert judgment") is an approximated way that does not use systematic computational procedures to assess the environmental profile of the system under study. This method requires thorough training and extensive knowledge. A decisive role is played by relevant experiences of the experts carrying out the evaluation.

5.1 Data quality indicators

Six indicators called "data quality indicators (DQIs)" were adopted as five indicators related to data, and another is related to methodology. Furthermore, the five data quality levels are defined (1 = very good to 5 = poor) as shown in the additional details shown in Table 5 (EC 2013). According to the DQIs, three have been used for the data representativeness without predefined requirements: technological representativeness, geographical representativeness, and time-related representativeness. In addition, other DQIs are completeness, parameter

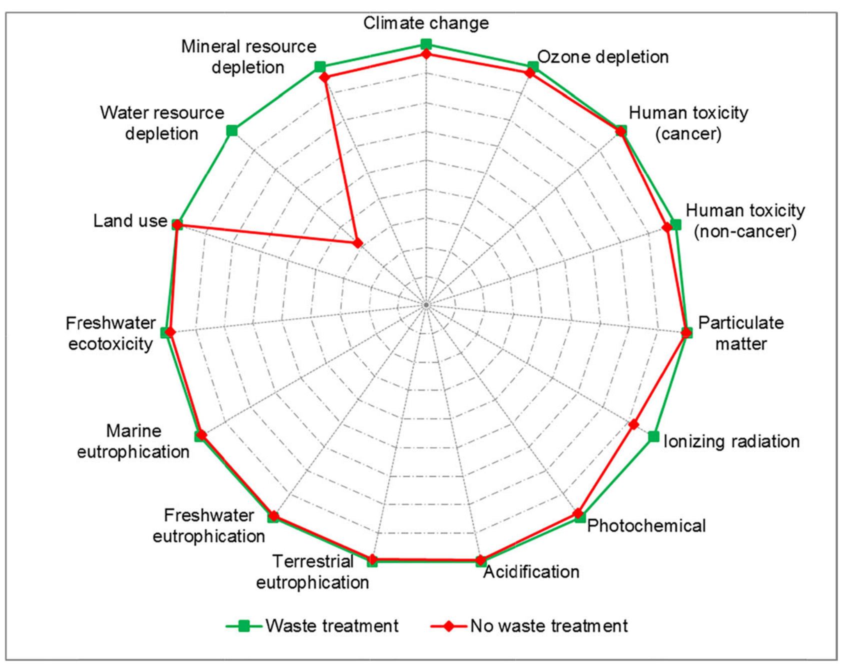

Fig. 3 A comparison of environmental burden between waste treatment and no waste treatment LCI data

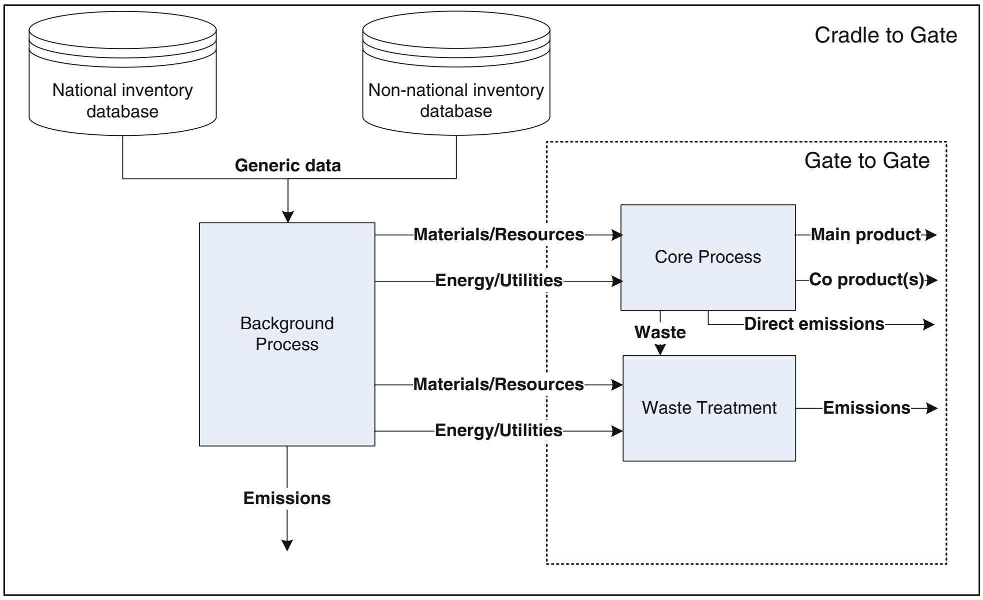

Fig. 4 Framework for improvement of the generic data for PEF study

uncertainty, and methodological appropriateness and consistency.

5.1.1 Technological representativeness (TeR)

The technology of process can be reflected in the true population of interest in the dataset based on the characteristics of technology, including enterprises, processes, and materials.

5.1.2 Geographical representativeness (GR)

For a true population with respect to geography, data from same or similar areas should be selected, e.g., the given location/site, region, country, market, continent, etc.

5.1.3 Time-related representativeness (TiR)

The age of data can reveal the specific conditions of the system. For times passed, the data used should probably not be re-used. Thus, the given year of data needs to be concerned. Based on the recommendations of the present study, data exceeding 10-year differences should not be used and needs to be updated. The intra-annual data is strongly recommended for PEF studies when data quality is concerned.

5.1.4 Completeness (C)

Completeness refers not only to an individual dataset, but the whole system is also considered. In this indicator, it is not easy to identify the level of quality. Thus, quality needs to be

Fig. 5 Uncertainty results from different frameworks of the Thai national LCI database

Uncertainty	
Before improving LCI creation	**After improving LCI creation**
Particulate matter	Water resource depletion
Climate change	Climate change
Acidification	Acidification
Water resource depletion	Particulate matter
Photochemical ozone formation	Photochemical ozone formation
Marine eutrophication	Human toxicity (non-cancer)
Terrestrial eutrophication	Freshwater ecotoxicity
Human toxicity (non-cancer)	Terrestrial eutrophication
Mineral resource depletion	Marine eutrophication
Human toxicity (cancer)	Land use
Freshwater ecotoxicity	Ozone depletion
Freshwater eutrophication	Human toxicity (cancer)
Land use	Mineral resource depletion
Ozone depletion	Ionizing radiation
Ionizing radiation	Freshwater eutrophication

Very low uncertainty
Low uncertainty
Fair uncertainty
High uncertainty
Very high uncertainty

Table 5 General template of data quality for generic data in the PEF pilot project in Thailand

Quality level	Quality rating	Completeness	Methodological appropriateness and consistency	Representativeness			Parameter uncertainty
				Time-related	Technological	Geographical	
Very good	1	≥90%	Attributional modeling and system boundary (no cutoff) include end of life modeling and multifunctionality	<3-year difference	Data from enterprises, processes, and materials under study	Data from same area as study	Very low uncertainty, ≤10%
Good	2	80–90%	Attributional modeling and system boundary with end of life modeling and multifuctionality	3 to 6-year difference	Average data on related processes or materials from mixed technology in which the technology under study is included	Average data from larger area in which the area under study is included	Low uncertainty, 10–20%
Fair	3	70–80%	Attributional modeling and system boundary with end of life modeling or multifuctionality	6 to 9-year difference	Data on related processes or materials but different technology OR data on different processes or materials but same technology	Average data from larger area in which the area under study is included	Fair uncertainty, 20–30%
Poor	4	50–70%	Attributional modeling and system boundary without end of life modeling and multifuctionality	10 to 12-year difference	Average data on related processes or materials from mixed technology in which the technology under study is excluded	Data from similar area in which the area under study is excluded	High uncertainty, 30–50%
Very poor	5	<50%	Attributional modeling but not meet the PEF requirements	Age of data unknown or more than 12 years of difference to our reference year (specific data)	Data from unknown OR distinctly different enterprises, processes, materials, and technology	Data from unknown OR distinctly different area	Very high uncertainty, >50% or unspecified

Table 6 Overall data quality level according to the achieved data quality rating

Overall data quality rating (DQR)	Overall data quality level
≤1.6	Excellent quality
1.6 to 2.0	Very good quality
2.0 to 3.0	Good quality
3.0 to 4.0	Fair quality

decided by an expert with respect to the coverage for each EF impact category and in comparison to an ideal data quality.

5.1.5 Parameter uncertainty (P)

Resource use and emission profiles are applied for parameter uncertainty. Qualitative expert judgment or relative standard deviation as a percentage employed the Monte Carlo simulation. In this pilot PEF study, the coefficient of variation (often abbreviated as CV or CoV) was calculated for uncertain data quality ratings by applying the simulation.

$$CV = \left(\frac{\sigma}{\mu}\right) \times 100 \tag{2}$$

where CV is defined as the ratio of the standard deviation (σ) to the mean (μ). The main purpose of the findings is used to measure the quality of the data by measuring the dispersion of the population data for a probability or frequency distribution. As a rule, a lower CV suggests a good model fit to the smaller residuals relative to the predicted value. On the contrary, higher CV describes larger sizes of the squared residuals and outcome values.

5.1.6 Methodological appropriateness and consistency (M)

It is the predefined criterion to evaluate the relation to the methodology, applied LCI methods, and methodological choices in line with the goal and scope of the entire dataset. Furthermore, it can be concluded that the method has been applied consistently across all data.

Guidance of data quality assessment applies for and specifies data. Generic data can be conducted at the level of input flows. Table 5 presents the data quality criteria applied in this pilot study. The quality assessment for generic data aimed to improve the dataset selection or encourage manufacturers to use the Thai national LCI database for environmental impact assessment.

5.2 Data quality rating

The results of data quality are represented in the data quality rating (DQR) and also used to identify the corresponding quality levels in Table 6. The overall data quality can be calculated by summing up the achieved quality rating for each of the quality criterion and dividing by six (the total number of criteria). Simply, the equation provides for the calculation below:

$$DQR = \frac{TeR + GR + TiR + C + P + M}{6} \tag{3}$$

Table 7 Examples of data quality rating for Thai dataset on climate change

Data quality indicators (DQIs)	Electricity mix; AC; consumption mix, at grid	Tap water, provincial water authority; chemical water treatment; production mix, at plant	Diesel; from crude oil; production mix; at refinery; 50 ppm sulfur
Technological representativeness: TeR	1	1	1
Geographical representativeness: GR	1	1	1
Time-related representativeness: TiR	2	2	3
Completeness: C	2	2	2
Parametric uncertainty: P	1	1	1
Methodological appropriateness and consistency: M	2	3	2
DQR	1.5	1.67	1.67
Data quality indicators: (DQIs)	Refrigerant R134a, at plant	Kraft paper, bleached, at plant	Sodium percarbonate, powder, at plant
Technological representativeness: TeR	2	2	2
Geographical representativeness: GR	3	1	3
Time-related representativeness: TiR	1	1	4
Completeness: C	3	3	3
Parametric uncertainty: P	3	2	2
Methodological appropriateness and consistency: M	4	3	4
DQR	2.67	2.00	3.00

Dataset	% Contribution on Impact Category	
Dataset A	40.00	Good
Dataset B	30.00	
Dataset C	15.00	Fair
Dataset D	5.00	
Dataset E	3.00	
Dataset F	3.00	
Dataset G	2.50	
Dataset H	1.50	
	100.00	

Fig. 6 Requirements for data quality

– TeR: technological representativeness
– GR: geographical representativeness
– TiR: time-related representativeness
– C: completeness
– P: precision/uncertainty
– M: methodological appropriateness and consistency

The aforementioned understanding helps to explain in Table 7 by giving examples for the scoring of each DQI and calculating the DQR.

Six datasets were indicated to find the data quality rating. Firstly, the DQR is at least 1.6, which corresponds to an overall excellent quality, so the DQR of the *electricity mix; AC; consumption mix, at grid* is less than 1.6. With excellent quality, the next DQR, namely *tap water, provincial water authority; chemical water treatment; production mix, at plant; diesel; from crude oil; production mix; at refinery; 50 ppm sulphur, and kraft paper, bleached, at plant* ranges from 1.6 to 2.0 for very good quality; Finally, the DQR of the *refrigerant R134a, at plant* and *sodium percarbonate, powder, at plant* ranges from 2.0 to 3.0 for good quality. Altogether, these datasets reveal the level of data quality to be at least good quality on climate change impact category. Thus, the PEF results are reliable.

5.3 Data quality assessment

The quality rating of the dataset should be "good" on a set of data that reveals high impact on each environmental category with at least two thirds of the remaining 30% (i.e., 20 to 30%) should be "fair." For instance, datasets A and B make the

Dataset		Climate change	DQR	Data quality level
Electricity mix; AC; consumption mix, at grid	97.69%	88.22	1.50	Excellent
Diesel; from crude oil; production mix; at refinery; 50 ppm sulphur		9.47	1.67	Very good
Sodium tripolyphosphate, at plant		1.21		
Kraft paper, bleached, at plant		0.75		
Refrigerant R134a, at plant		0.22		
Tap water, provincial water authority; chemical water treatment; production mix, at plant		0.13		

Dataset		Ozone depletion	DQR	Data quality level
Refrigerant R134a, at plant	98.93%	55.18	2.83	Good
Diesel; from crude oil; production mix; at refinery; 50 ppm sulphur		43.75	2.33	Good
Electricity mix; AC; consumption mix, at grid		0.68		
Kraft paper, bleached, at plant		0.20		
Sodium tripolyphosphate, at plant		0.18		
Tap water, provincial water authority; chemical water treatment; production mix, at plant		0.01		

Dataset		Human toxicity (cancer)	DQR	Data quality level
Sodium tripolyphosphate, at plant	94.24%	66.71	3.50	Fair
Electricity mix; AC; consumption mix, at grid		14.46	2.00	Very good
Diesel; from crude oil; production mix; at refinery; 50 ppm sulphur		13.07	2.33	Good
Kraft paper, bleached, at plant		5.20		
Tap water, provincial water authority; chemical water treatment; production mix, at plant		0.44		
Refrigerant R134a, at plant		0.12		

Dataset		Water resource depletion	DQR	Data quality level
Tap water, provincial water authority; chemical water treatment; production mix, at plant	93.64%	86.64	1.67	Very good
Diesel; from crude oil; production mix; at refinery; 50 ppm sulphur		7.01	1.67	Very good
Sodium tripolyphosphate, at plant		3.07		
Kraft paper, bleached, at plant		2.36		
Electricity mix; AC; consumption mix, at grid		0.87		
Refrigerant R134a, at plant		0.05		

Dataset		Mineral resource depletion	DQR	Data quality level
Diesel; from crude oil; production mix; at refinery; 50 ppm sulphur	93.01%	60.98	2.33	Good
Electricity mix; AC; consumption mix, at grid		14.22	1.83	Very good
Refrigerant R134a, at plant		9.79	2.50	Good
Sodium tripolyphosphate, at plant		8.01	3.50	Fair
Kraft paper, bleached, at plant		6.65		
Tap water, provincial water authority; chemical water treatment; production mix, at plant		0.34		

Fig. 7 Example of data quality assessment for Thai datasets

greatest contribution to the impact category (i.e., at least 70%). Furthermore, at least a good DQR is required as shown in Fig. 6. However, the data quality is used for data improvement. Thus, investigators need to bear in mind a correct representation of the facts. The results of quality assessment can reveal both general and specific gaps to be managed in the future. On the other hand, without any gaps appearing, the data improvement would be difficult to achieve.

In reality, the assessment of data quality has to be applied in each impact category where some datasets might be reliable on certain impacts but not on others. Figure 7 exemplifies the differences in level of data quality with environmental impact. As a result, electricity mix; AC; consumption mix, at grid requires at least a good quality level on climate change, human toxicity (cancer), and mineral resource depletion. Then, ozone depletion needs good quality from both refrigerant R134a, at plant and diesel; from crude oil; production mix; at refinery; 50 ppm sulfur. On the contrary, water resource depletion requires only good quality from tap water, provincial water authority; chemical water treatment; production mix, at plant. As an example, consider that the DQR of sodium percarbonate, powder, at plant on human toxicity (cancer) discloses fair quality level. Thus, this impact category offers less confidence on the PEF results because sodium percarbonate, powder, at plant is a significant contribution. It would be better to improve the quality of data before using or changing to other representative data providing a good quality level.

In essence, in the course of preparing and improving the Thai national LCI database, the datasets were also found to comply with PEF in more compliance areas. Table 8 demonstrates the improvement of the Thai national database against the PEF, even though gaps remain.

6 Conclusions

Although the Thai national LCI reveals many points of data gaps, the gaps are believed to be capable of contributing to improved quality. The data quality assessment cannot change the quality of LCI data but can ensure efficient and reliable LCA results. On the other hand, the potential LCI should present the environmental performance of products with accuracy and precision. An appropriate procedure on developing the quality of LCI data needs to be considered, because it can be used to sustain the LCI data that is internationally acceptable and also serve as the basis for compatibility of databases worldwide, including the national database. According to the results and experiences with LCI improvement, even small issues, e.g., non-representative data and untreated waste, have been found to be capable of setting the wrong direction of interpretation for environmental performance

Table 8 Results of compliance analysis of the Thai national database against the PEF after adjusting the quality of data

Compliance area	Product Environmental Footprint	Compliance with PEF
Documentation	• ILCD format to be used	• Yes
	• Minimum documentation extent specified	• Yes
Nomenclature	• Compliance with ILCD nomenclature document (e.g., elementary and product flow naming, prescribed flow properties and unit groups/units for flows, classification naming, etc.).	• No (partial)
	• Use of ILCD reference elementary flows	• No
	• Only certain aggregated elementary flows (e.g., VOC) are permitted	• No
	• PEF terminology to be used	• No (partial)
Data quality	Achieved data quality levels to be provided (subject to review) on: • Technological representativeness	• Yes
	• Geographical representativeness	
	• Time-related representativeness	
	• Completeness	
	• Parameter uncertainty	
	• Methodological appropriateness and consistency	
	• Overall quality	
	Note: Data quality levels are well-defined	
Method	• PEF or PECR methodology compliance	• No (partial)
	• Mandatory LCIA methods fixed	• Yes
Review	• Review by “qualified reviewer” as defined in PEF guide	• Yes
	• Separate review report	• Yes

of products. At present, the improvement of the creation of generic data for this PEF study is illustrated in Fig. 4. Moreover, the results in Table 8 demonstrate the results of the compliance analysis of Thai national datasets after improvement. According to the findings, some compliance areas have been solved, while others have been partially handled. Hence, the recommendations are presented as follows:

- Data quality assessment cannot increase the quality of data, but it can reflect the reality of dataset quality.
- Without data quality assessment, the results of environmental impact are unreliability. It is important to consider the quality of data in the interpretation phase of LCI and LCA studies in order to determine the confidence in the results.
- Different impact categories require different sets of data quality, in which some datasets reveal good results for one, but poor for others.
- The quality of dataset depends not only on specific (foreground) data, but the generic (background) data is the key point of concern.
- Data quality assessment is aimed at improvement; thus, there is no need to show the data gaps and attempt to close those gaps. Without gaps, questions arise about how to improve data quality.
- It is better to apply data quality assessment in the beginning stages of LCA, which can also be improved later.

The investigators would like to suggest that the environmental impacts would be better to be concerned with respective the quality of data. In reality, the issues that have been demonstrated in Table 1 need to be handled, and the data quality needs to be improved for the Thai national LCI database in order to achieve the PEF requirements and also aim to support the generic data for Thai industries and companies.

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